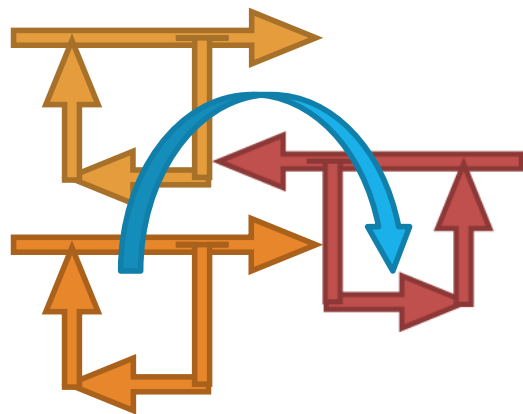


Control Co-Design for Wind/Tidal/Wave Energy Systems



Dr. Mario Garcia-Sanz
Program Director, ARPA-E
U.S. Department of Energy

July 26, 2018

Sequential...

- The increasing **complexity** of technology has changed the way we study engineering.
Engineering **careers** are now much more **specialized**.

- New **engineers**:
 - have a deeper knowledge of some aspects
 - at the cost of a much **narrower picture!!**

- Consequences:
 - **Sequential way of working** in industry
 - **Control** = algorithms/circuits to regulate **existing** systems

- This sequential approach **limits** the **possibilities** of the design.

Myopic approach

Each step limits the next one

Aerodynamics



Mechanical/
Structural



Electrical



Electronics

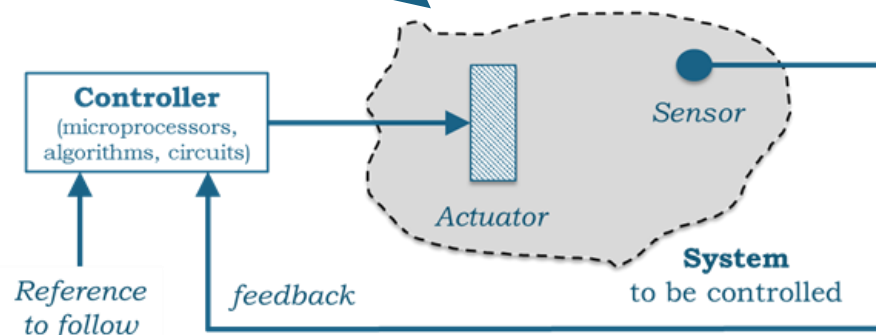


Controls

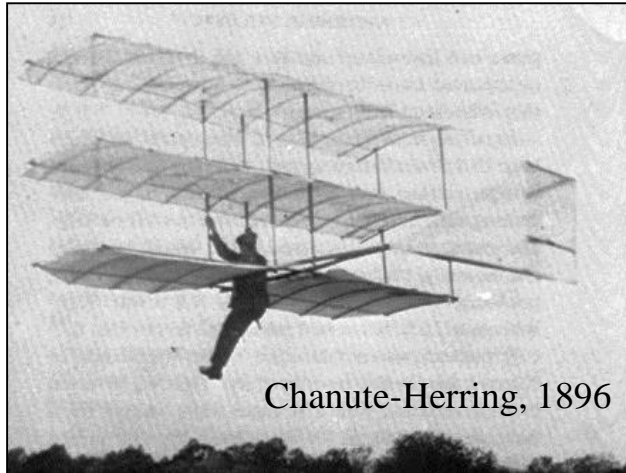


PIDs...

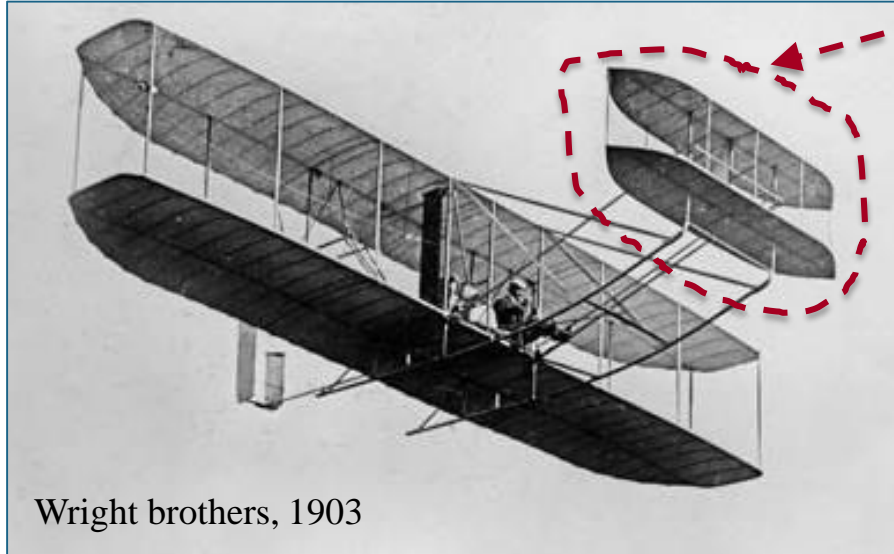
Control at the end



Concurrent...

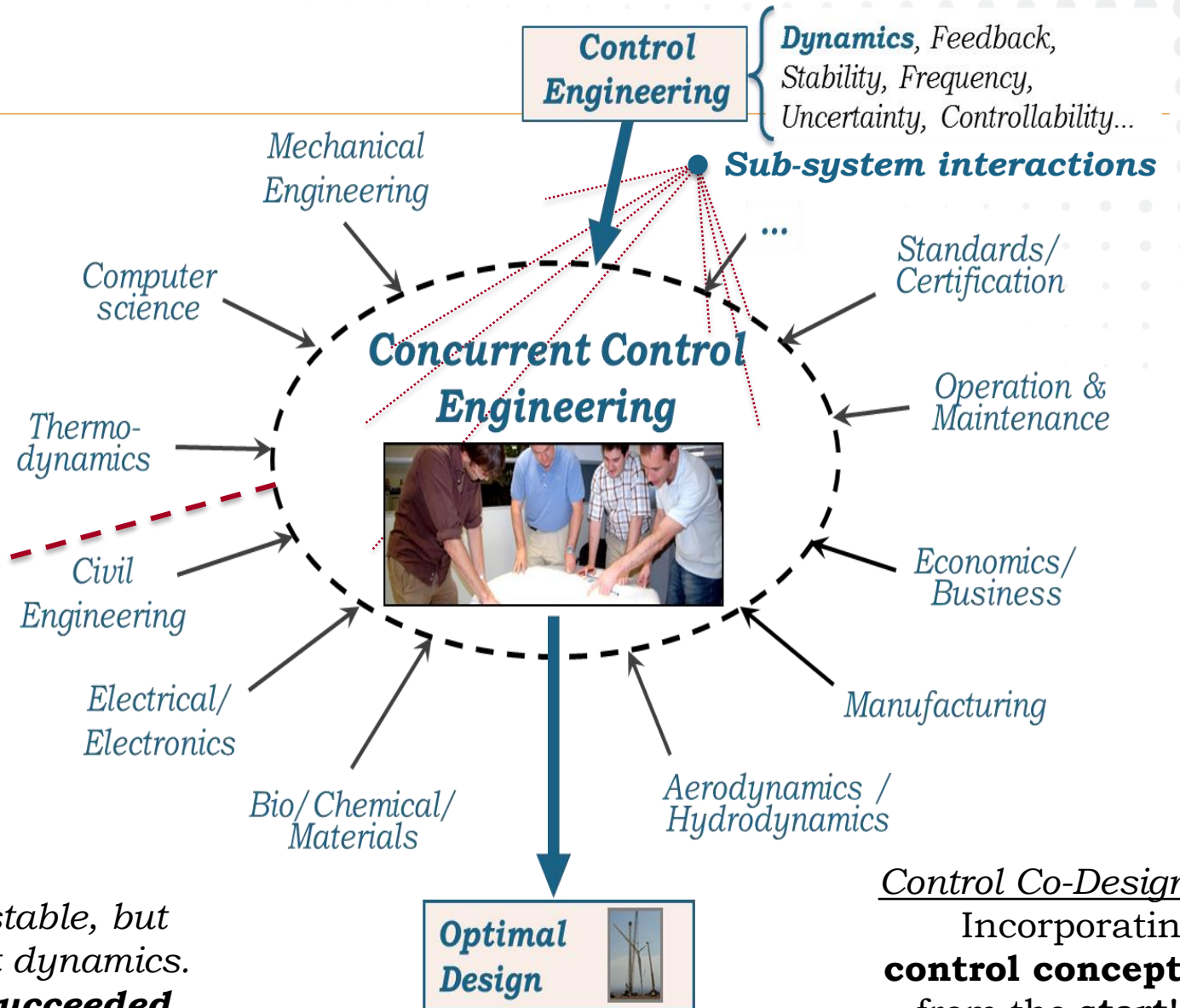


*Stable, but
slow dynamics.
It failed*

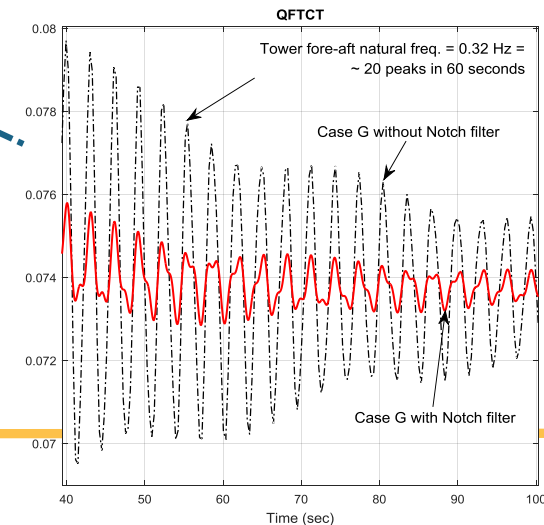
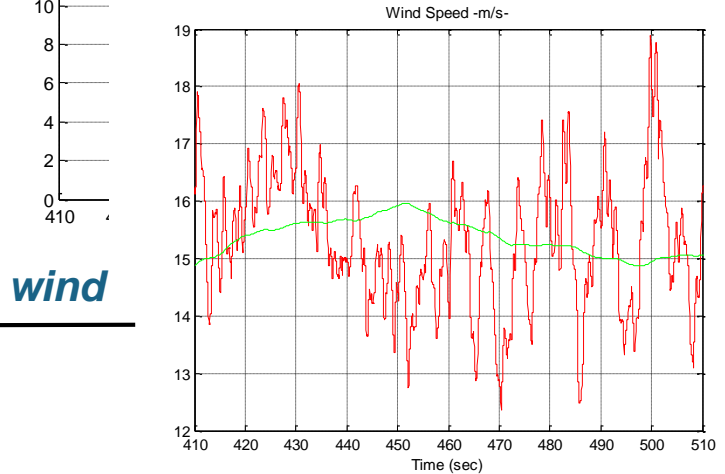
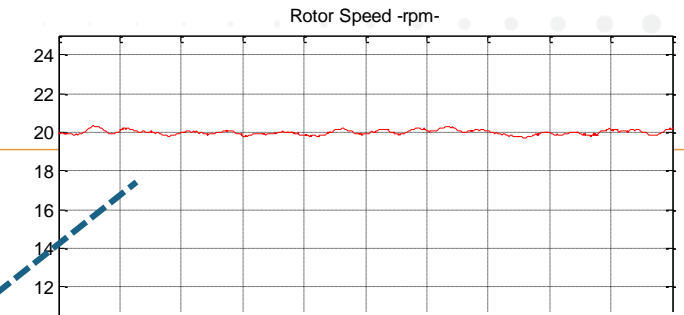
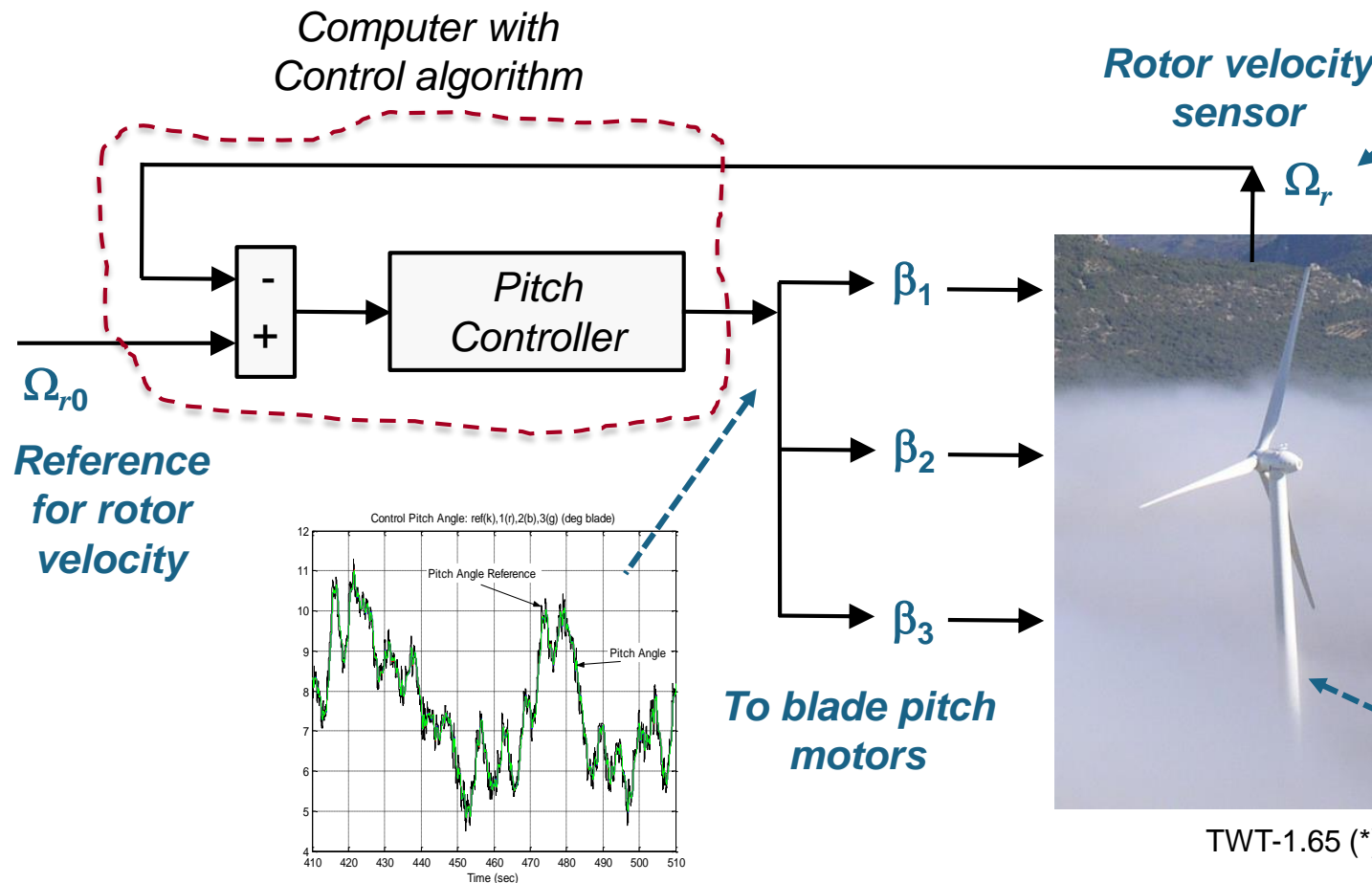


Wright brothers, 1903

*Unstable, but
fast dynamics.
It succeeded*



Example. Wind turbine design



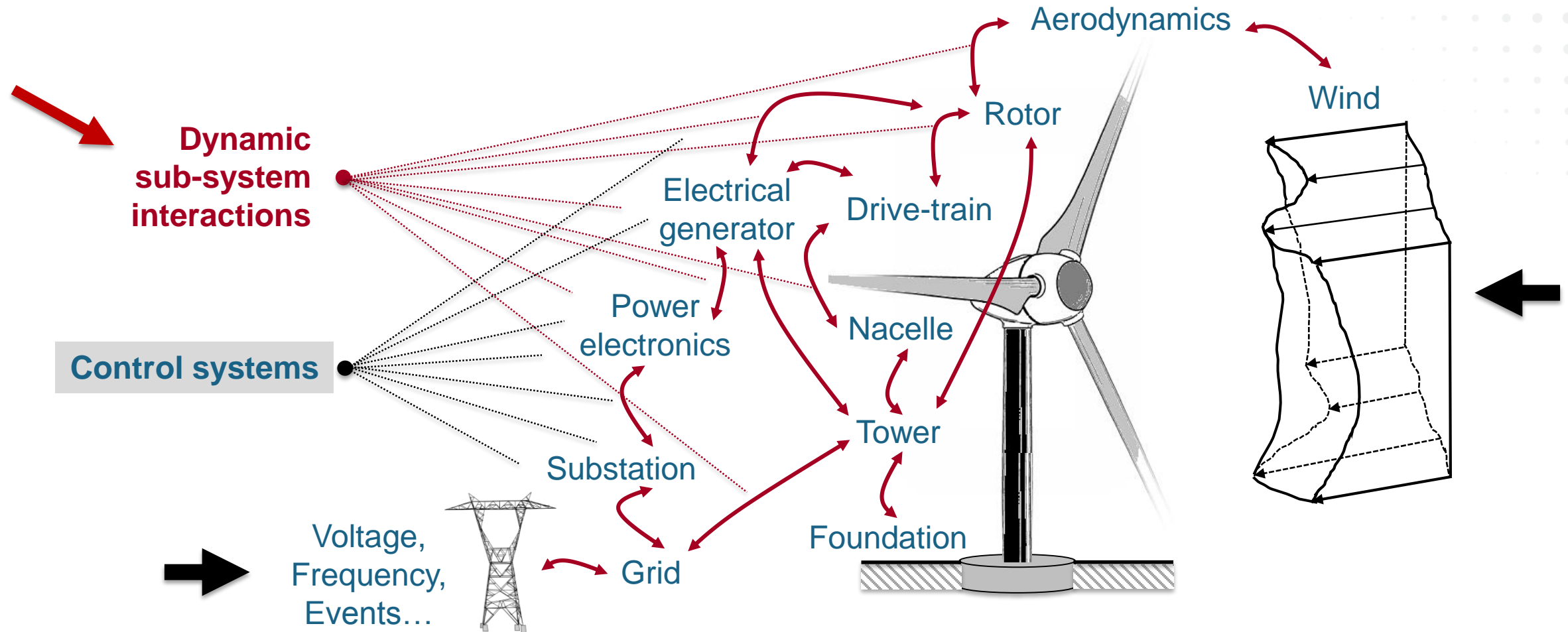
Reducing Tower vibration

To reduce tower cost

Rotor speed control system
varying blade pitch angle to control rotor speed

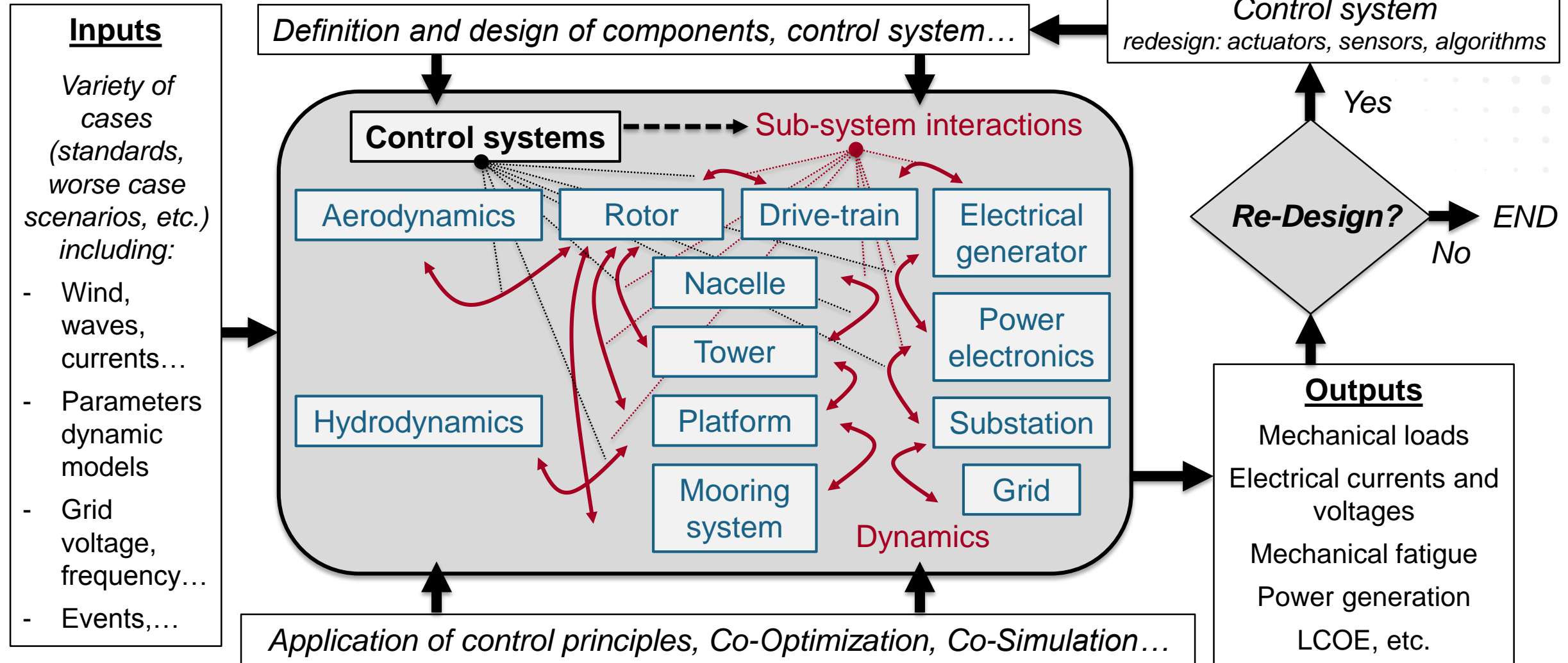
(*) Garcia-Sanz, M. *Robust Control Engineering: Practical QFT Solutions*. (Boca Raton, Florida: CRC Press, 2017), 317-342.

Sub-system interactions. Dynamics/Control

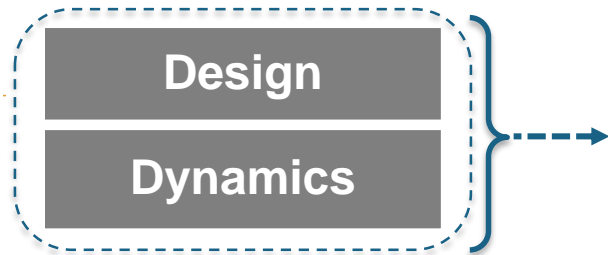


More dynamic coupling = More need of Control Co-Design!!!

Control Co-Design. Methodologies



For systems that involve both:



Control Co-Design Program

for Wind & Marine Hydro-Kinetic

Objectives:

To incorporate concurrent control engineering **design philosophy** in the energy sector.

To develop **computer tools** to facilitate the control co-design philosophy.

To develop new **energy solutions** and products that were not achievable otherwise.

Definition:

Control Co-Design =

Concurrent Control Engineering for Optimal System Design

Area 1

Wind

Hydro-kinetic

Offshore Floating WT

Offshore Bottom-fixed WT

Onshore WT

Airborne WT

Wind Farms

Tidal Energy

Stream/River Energy

Wave Energy

Hybrid Systems

Wave, Tidal Farms

Large sub-system interactions

- Aerodynamics
- Hydrodynamics
- Mechanical structures
- Drive-trains
- Electrical generators
- Power electronics
- Grid
- Etc.

Control concepts: Limitations (Bode), Frequency resp., Root locus, Robust., MIMO.

Co-optimization: Simultaneous, Lagrange-based, AI, ML.

Co-simulation: Iterative, Nested/Bi-level.



ARPA-E hard

Control Co-Design. Opportunities

$$LCOE = \frac{FCR * CapEx + OpEx + DecEx}{AEP}$$

1. Mass reduction

- Mechanical fatigue reduction
- Flexible materials...

2. Survivability

- Extreme weather
- Maximum loads, Events...

3. Resiliency

- Fault-tolerance, Self-healing
- Time to recover

4. Efficiency

- Aerodynamic
- Mechanical, Electrical

5. O&M

- Operation costs
- Maintenance costs

6. Components Replacement

- Time between failure
- Access, costs

7. Performance decline

- Over the years
- Corrosion, aging...

8. Installation

- Vessels, strategies to reduce cost
- Self-deployment

9. Grid integration

- Frequency, voltage
- Active/reactive power

10. Off-grid opportunities

- Substituting diesel
- Other applications

11. Environmental friendly

- Noise, aspect...
- Birds, fish impact

12. Subsystem interactions

- Dynamic coupling
- Control solutions

13. New paradigms

- Nature inspired?
- Control, sensors, act.

14. Hybrid systems

- Wind + Wave
- + Tidal + Solar...

15. Software development

- Co-Optimization
- Co-Simulation

LCOE analysis

$$LCOE = \frac{FCR * CapEx + OpEx + DecEx}{AEP}$$

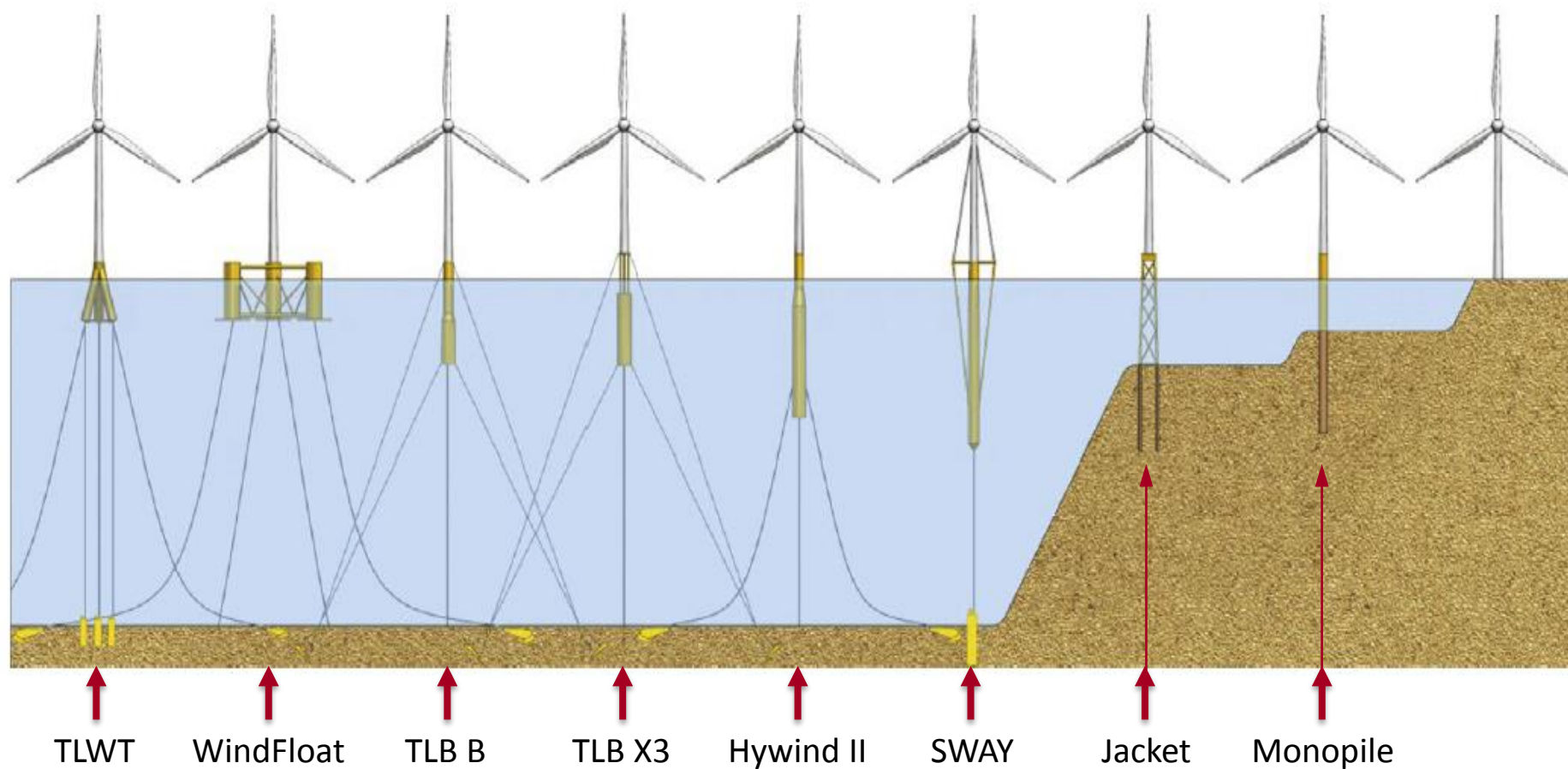
1. Offshore Floating + Bottom-Fixed Wind Turbines

- Comparison of (6 + 2) cases: 5 MW turbine, 100 machine farm
 - FWT: *Floating Wind Turbines*: Tension-Leg-Buoy (**TLB B** and **X3**), Spar-Buoy (**Hywind**), Semi-Sumergible (**WindFloat**), Tension-Leg-Spar (**SWAY**), Tension-Leg-Wind-Turbine (**TLWT**)
 - BFWT: *Bottom-Fixed Wind Turbines* (**Jacket** and **Monopile**)

2. Marine Hydro-Kinetic Energy Converters

- Comparison of 6 reference models
 - *Hydrokinetic turbines*:
Tidal **RM1**, Ocean **RM4**, River **RM2**
 - *Wave Energy Converters*:
Point absorber **RM3**, Surge Wave **RM5**, Water Column **RM6**

LCOE: Offshore Floating + Bottom-Fixed Wind Turbines (I)



CASE STUDY

(a) Turbine:

Turbine rated power 5 MW
Turbine rotor diameter 126 m
Turbine hub height 90 m
Water depth 200 m for floating
and 30 m for bottom-fixed

(b) Farm:

500-MW project size (100 WTs)
Distance from shore 200 km

(c) AEP:

45.7% Capacity factor
Losses: Wake 7%, Grid 1.8%,
Availability 93.8%, Other 9%.
3,125 h/year at rated power

(d) Economics:

FCR of 10%

[1]. A. Myhr, C. Bjerkseter, A. Ågotnes, T. Nygaard, *Levelised cost of energy for offshore floating wind turbines in a life cycle perspective*, Renewable Energy, Vol. 66, pp. 714-728, June 2014.

[2]. J. Jonkman, S. Butterfield, W. Musial, and G. Scott, *Definition of a 5-MW Reference Wind Turbine for Offshore System Development*. Technical Report NREL/TP-500-38060, February 2009.

LCOE: Offshore Floating + Bottom-Fixed Wind Turbines (II)

Name	LCOE (cts\$/kWh) with export cables 200 km	M\$ per 5 MW turbine in a 500 MW farm (100 machines)			% of CAPEX that is:		
		CAPEX (M\$)	OPEX (M\$/yr)	DECEX (M\$ last yr)	Steel cost	Mooring System Cost water depth 200 m	Installation Cost Turbine, Substructure and Mooring System
TLWT	16.10	18.25	0.66	0.66	46.21	9.88	5.30
WindFloat	18.90	23.00	0.66	-0.10	65.11	2.72	3.67
TLB B	15.50	17.50	0.66	0.65	48.05	10.96	5.53
TLB X3	15.60	17.75	0.66	0.63	48.86	11.04	5.45
Hywind II	16.50	19.00	0.66	0.26	59.03	2.43	5.19
SWAY	16.00	18.25	0.66	0.36	56.03	8.91	4.68
Jacket	16.10	18.75	0.58	1.42	56.83	0.00	10.41
Monopile	15.30	17.50	0.58	0.97	56.43	0.00	8.79

$$LCOE = \frac{FCR * CapEx + OpEx + DecEx}{AEP}$$

Control Co-Design
"Control to substitute materials"

Hypothesis: Control Co-Design benefits
--to discuss today--

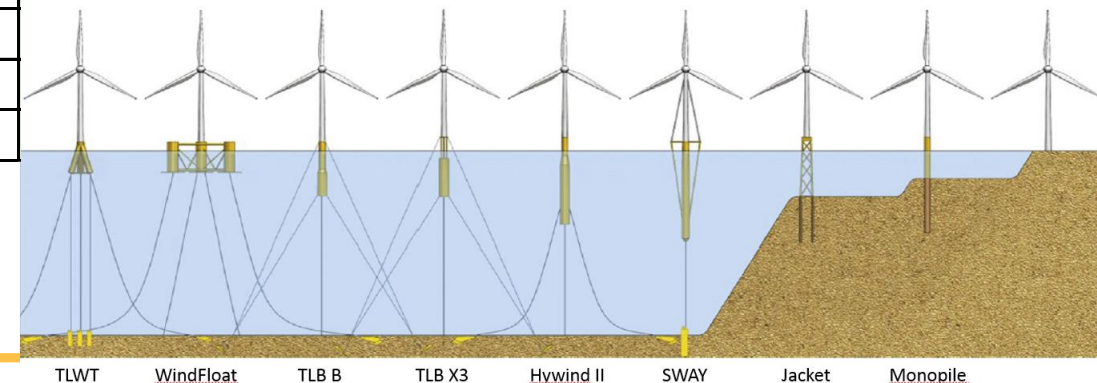
Steel cost: \$1000 per ton

Losses reduction:

- Turbulence losses, from 6% to 2%
- Array losses, from 7% to 2%
- Turbine availability, from 93.8% to 97%
- Other losses, from 3% to 1.5%

Operation & maintenance: 15% improvement

Mass reduction: from 0% to 60%



LCOE: Offshore Floating + Bottom-Fixed Wind Turbines (III)

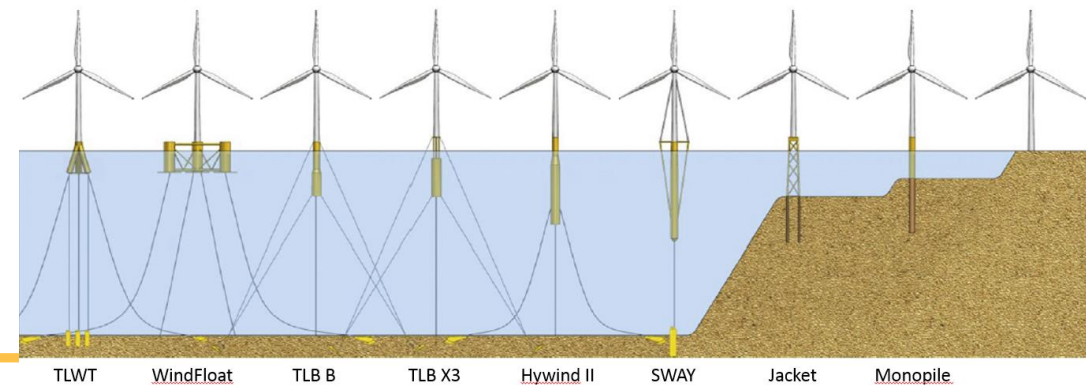
Given previous assumptions we obtained:

		M\$ per 5 MW turbine in a 500 MW farm (100 machines)			% of CAPEX that is:			Effects of Control Co-Design. LCOE reduction (%)						
Name	LCOE (cts\$/kWh) with export cables 200 km	CAPEX (M\$)	OPEX (M\$/yr)	DECEX (M\$ last yr)	Steel cost	Mooring System Cost water depth 200 m	Installation Cost Turbine, Substructure and Mooring System	Mass reduction = 50%		Effect of turbulence and wake control (efficiency) on LCOE (%)	OPEX reduction = 15%		Total effect on LCOE. Best case scenario (%)	
								Effect of mass reduction on LCOE (%)			Effect of OPEX reduction on LCOE (%)			
								with export cables	without export cables	with export cables	without export cables	with export cables	without export cables	
TLWT	16.10	18.25	0.66	0.66	46.21	9.88	5.30	22.29	24.10	15.02	3.91	4.23	41.22	43.35
WindFloat	18.90	23.00	0.66	-0.10	65.11	2.72	3.67	27.87	29.77	15.02	3.33	3.56	46.22	48.35
TLB B	15.50	17.50	0.66	0.65	48.05	10.96	5.53	23.17	25.11	15.02	4.03	4.37	42.22	44.50
TLB X3	15.60	17.75	0.66	0.63	48.86	11.04	5.45	23.56	25.52	15.02	3.99	4.32	42.58	44.86
Hywind II	16.50	19.00	0.66	0.26	59.03	2.43	5.19	24.65	26.61	15.02	3.83	4.13	43.50	45.76
SWAY	16.00	18.25	0.66	0.36	56.03	8.91	4.68	25.43	27.51	15.02	3.93	4.25	44.38	46.78
Jacket	16.10	18.75	0.58	1.42	56.83	0.00	10.41	25.00	27.02	15.02	3.42	3.70	43.44	45.74
Monopile	15.30	17.50	0.58	0.97	56.43	0.00	8.79	24.04	26.12	15.02	3.63	3.95	42.70	45.09

Control Co-Design “Control to substitute materials”

[1]. A. Myhr, C. Bjerkseter, A. Ågotnes, T. Nygaard, *Levelised cost of energy for offshore floating wind turbines in a life cycle perspective*, Renewable Energy, Vol. 66, pp. 714-728, June 2014.

[2]. J. Jonkman, S. Butterfield, W. Musial, and G. Scott, *Definition of a 5-MW Reference Wind Turbine for Offshore System Development*. Technical Report NREL/TP-500-38060, February 2009.

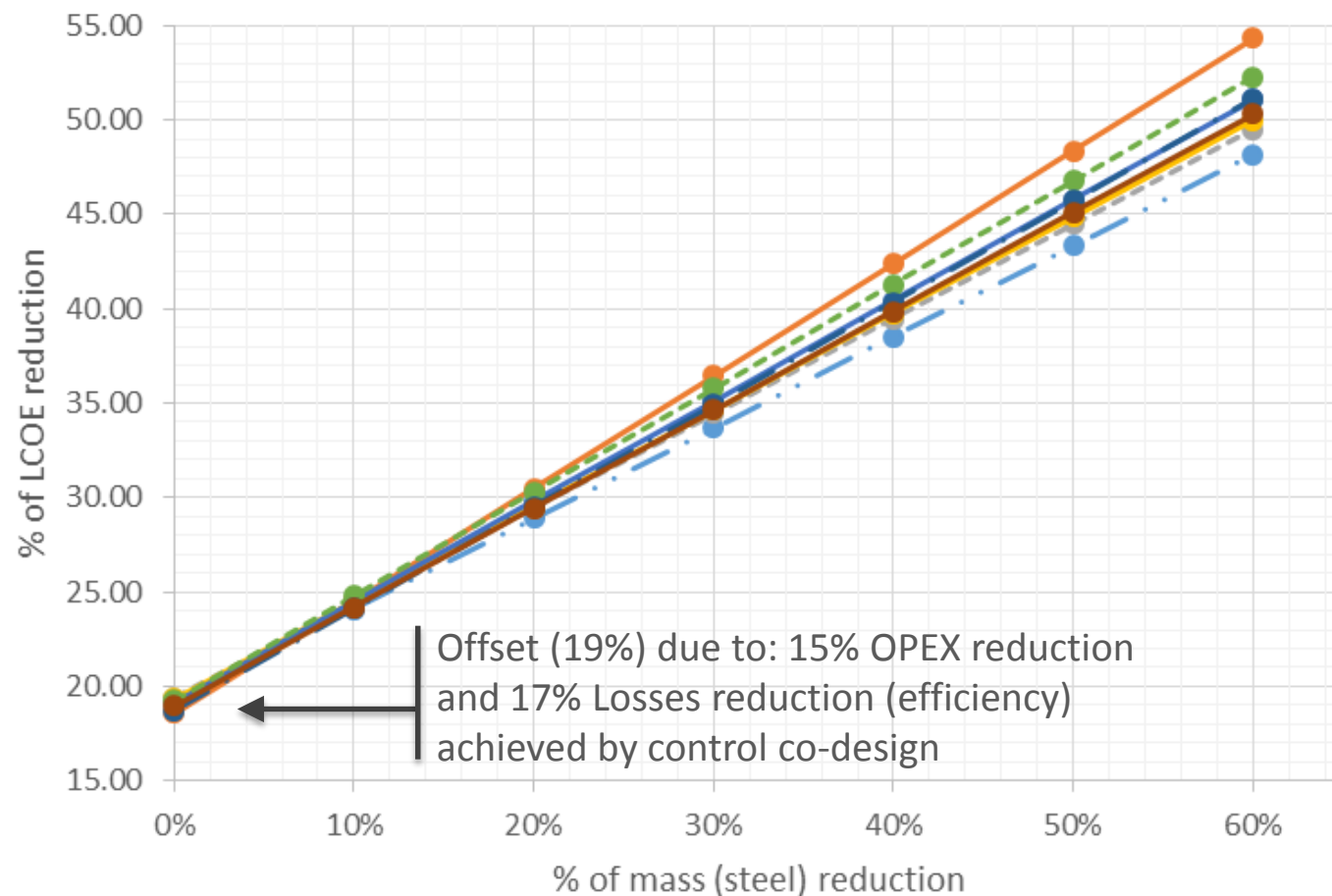


LCOE: Offshore Floating + Bottom-Fixed Wind Turbines (IV)

Given previous assumptions we obtained:

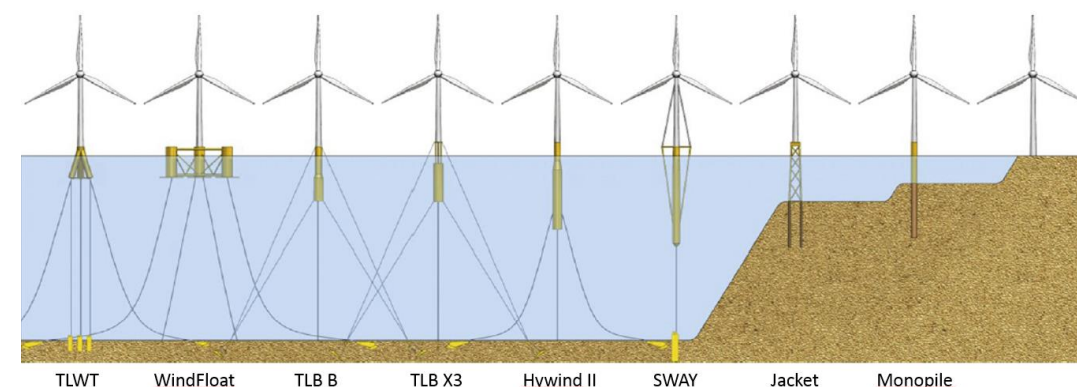


Effect of Control Co-Design on FWT & BFWT (no export cables)



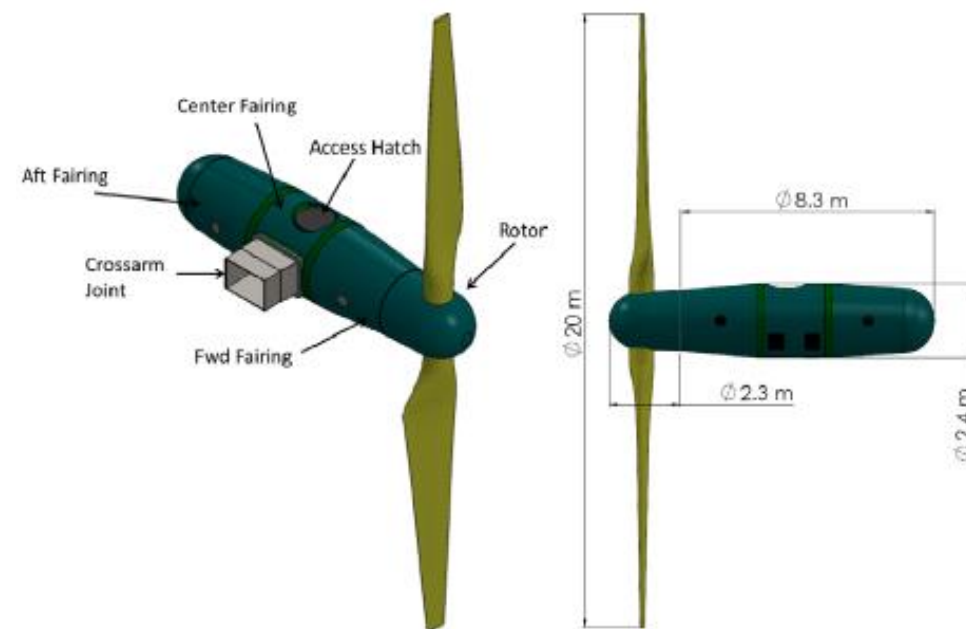
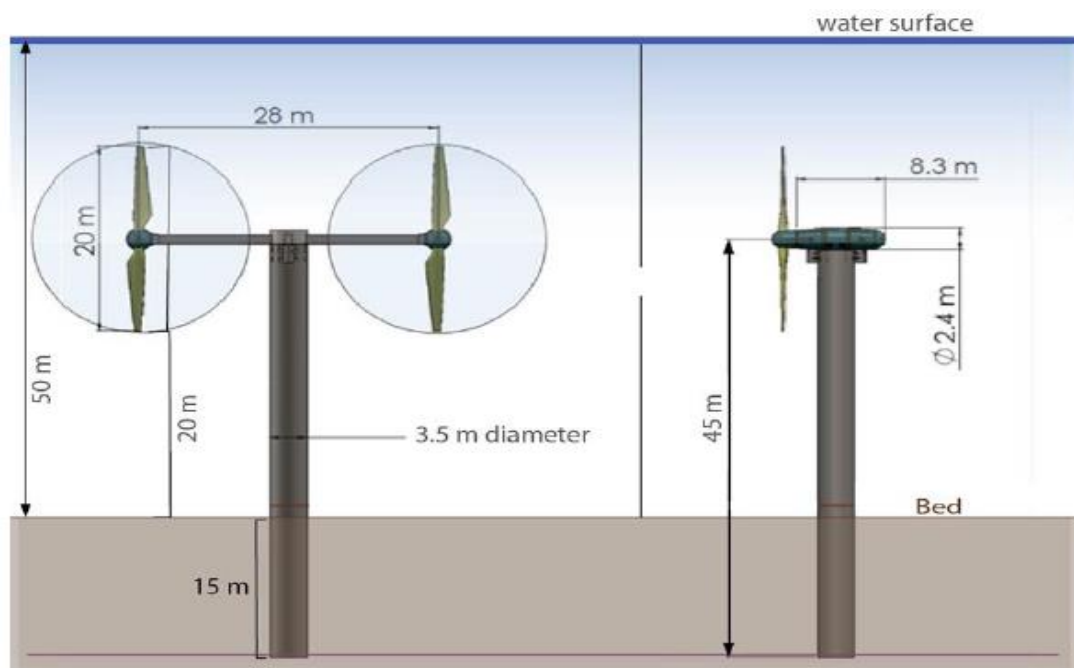
Control Co-Design
"Control to substitute materials"

DISCUSSION, COMMENTS?



LCOE: Tidal energy converters (I)

RM1: Tidal Turbine



CASE STUDY

(a) Turbine:

Rated power for each turbine 0.55 MW
Turbine rotor diameter 20 m
Seafloor to hub height 30 m
Water depth 50 m

(b) Farm:

110-MW project size
(100 towers, 200 turbines)
Distance from shore < 1 km

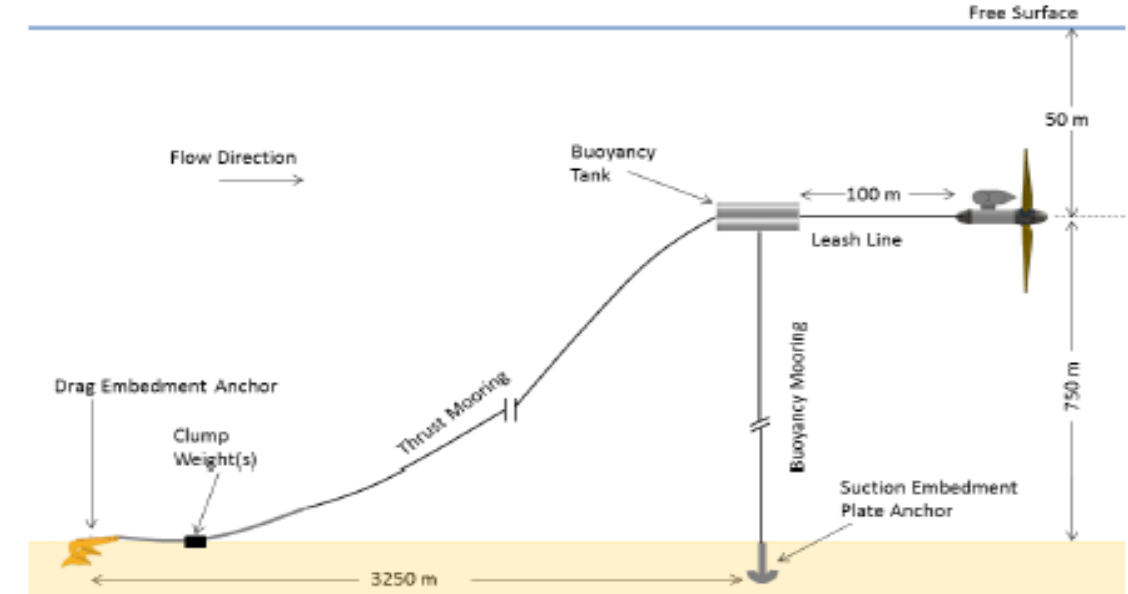
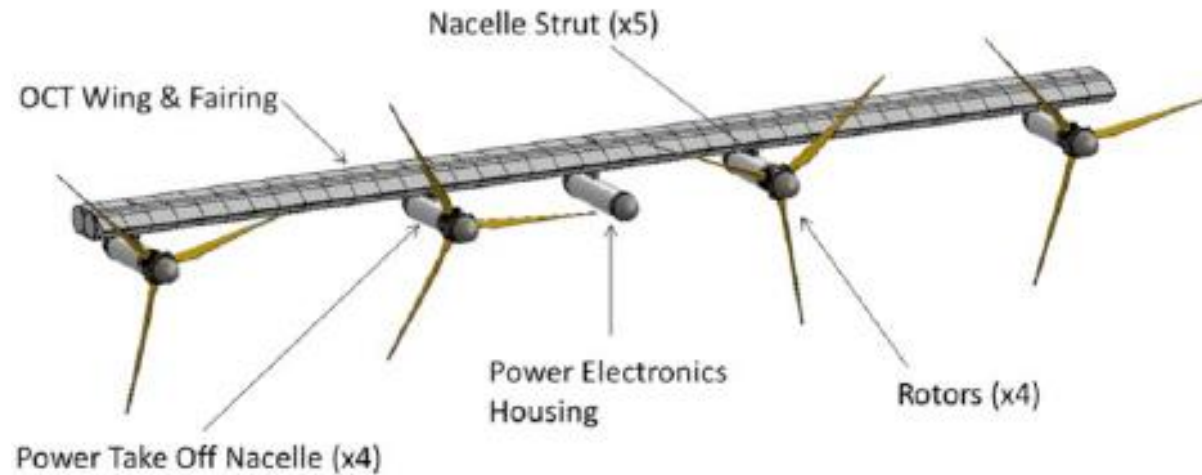
(c) AEP:

30% Capacity factor
Losses: Wake 0%, Grid 2%,
Availability 95%, Other 0%.
2,447 h/year at rated power

(d) Economics:
FCR of 10%

LCOE: Tidal energy converters (II)

RM4: Ocean Turbine



CASE STUDY

(a) Turbine:

Rated power for 1 turbine 1 MW
Turbine rotor diameter 33 m
Seafloor to hub height 750 m
Water depth 800 m

(b) Farm:

400-MW project size
(100 machines, 400 turbines)
Distance from shore 30 km

(c) AEP:

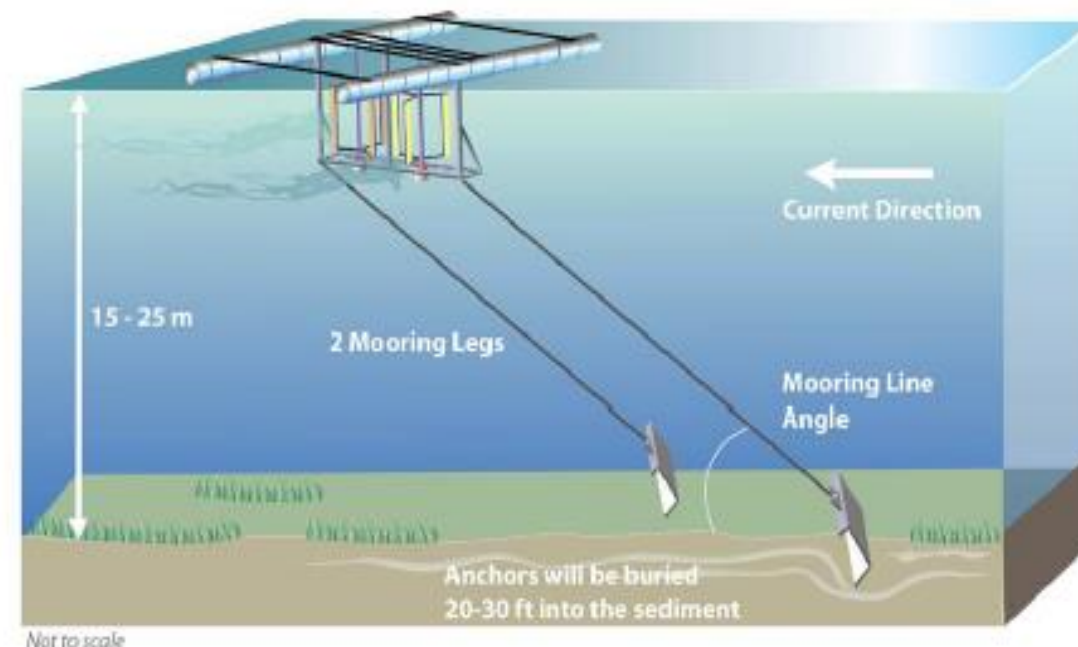
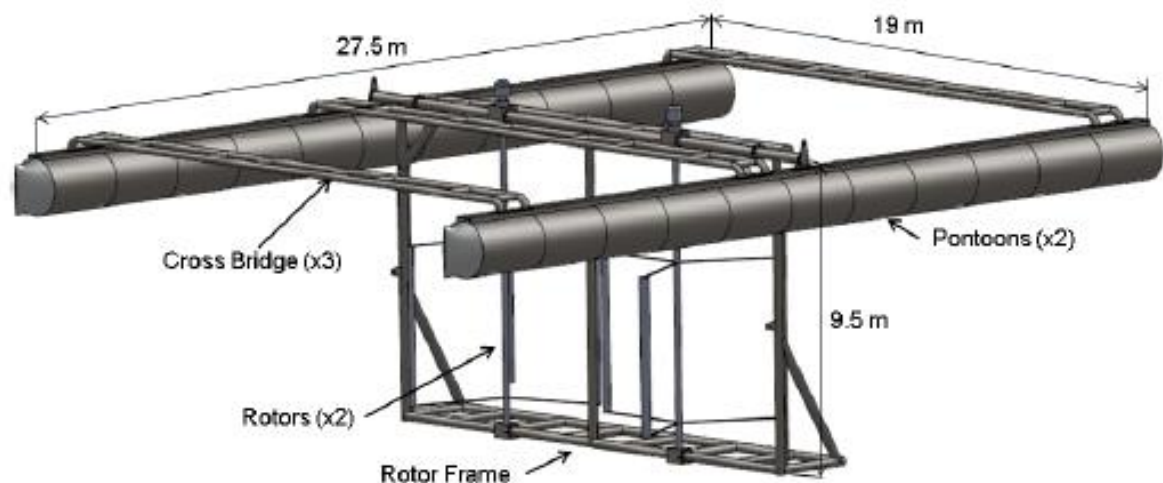
70% Capacity factor
Losses: Wake 0%, Grid 2%,
Availability 95%, Other 0%.
5,709 h/year at rated power

(d) Economics:

FCR of 10%

LCOE: Tidal energy converters (III)

RM2: River Turbine



CASE STUDY

(a) Turbine:

Rated power for 1 turbine 45 kW
Turbine rotor diameter 6.4 m
Seafloor to rotor height 11-21 m
Water depth 15-25 m

(b) Farm:

9-MW project size
(100 machines, 200 turbines)
Distance from shore < 1 km

(c) AEP:

28% Capacity factor
Losses: Wake 0%, Grid 2%,
Availability 95%, Other 0%.
2,284 h/year at rated power

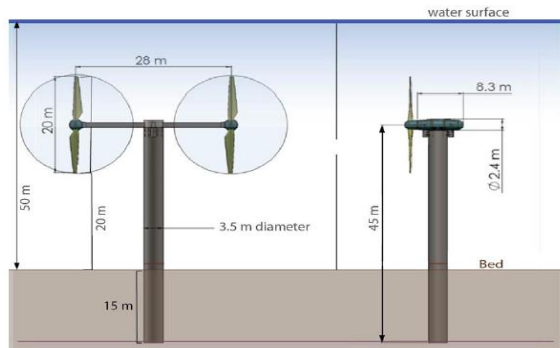
(d) Economics:
FCR of 10%

LCOE: Tidal energy converters (IV)

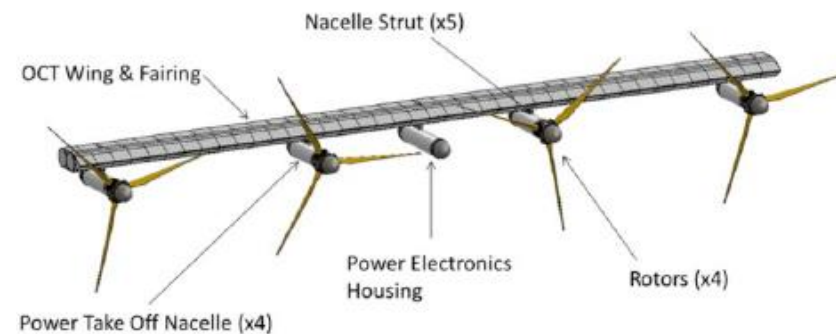
Control Co-Design
"Control to substitute materials"

Given previous assumptions we obtained:

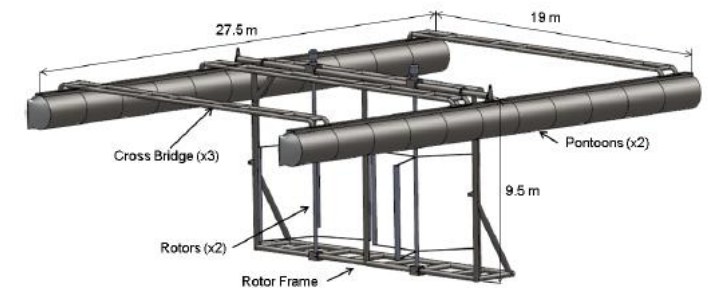
				M\$ per machine in a 100 machines farm			% of CAPEX that is:			Effects of Control Co-Design. LCOE reduction (%)			
	Name	LCOE (cts\$/kWh) with export cables 0-30 km	Power per machine (kW)	CAPEX (M\$)	OPEX (M\$/yr)	DECEX (M\$ last yr)	Steel cost	Mooring System Cost water depth 20-750 m	Installation Cost Turbine, Substructure and Mooring System	Effect of 50% mass reduction on LCOE (%)	Effect of turbulence and wake control (efficiency) on LCOE (%)	Effect of OPEX reduction of 15% (fatigue attenuation) on LCOE (%)	Total effect on LCOE. Best case scenario (%)
RM1	Tidal Turbine	18.10	1100	3.53	0.09	0.40	49.22	0.00	7.47	21.40	5.60	3.03	30.03
RM4	Ocean Turbine	15.20	4000	24.88	0.68	1.86	43.12	7.21	2.26	20.05	5.60	3.13	28.78
RM2	River Turbine	36.00	90	0.50	0.02	0.03	43.57	4.32	4.15	19.06	5.60	3.72	28.38



RM1



RM4

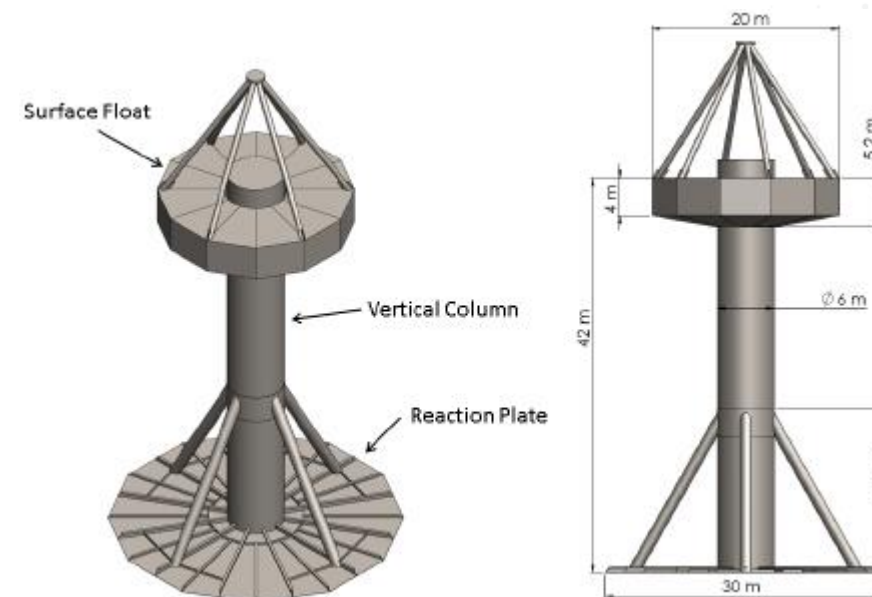
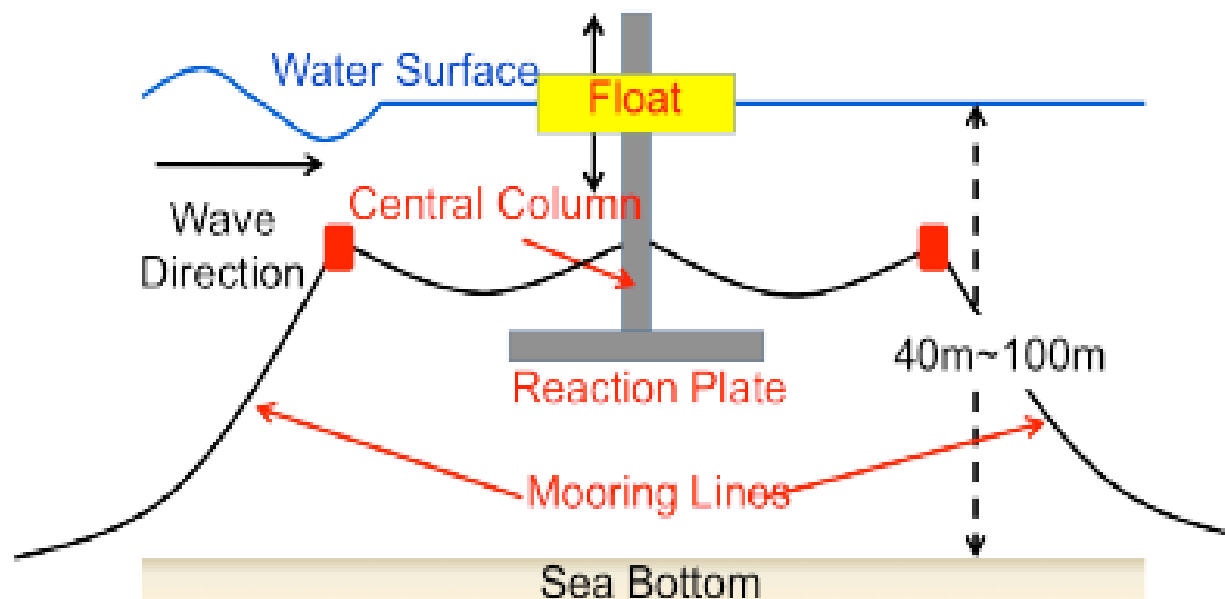


RM2

[1]. Vincent S. Neary, Mirko Previsic, et al., *Methodology for Design and Economic Analysis of Marine Energy Conversion (MEC) Technologies*. Technical Report SAND2014-9040, March 2014.

LCOE: Wave energy converters (I)

RM3: Wave Point Absorber



CASE STUDY

(a) Turbine:

Rated power for 1 machine 286 kW
Float diameter 20 m
Central column height 42 m
Water depth 40-100 m

(b) Farm:

28.6-MW project size
(100 machines)
Distance from shore < 30 km

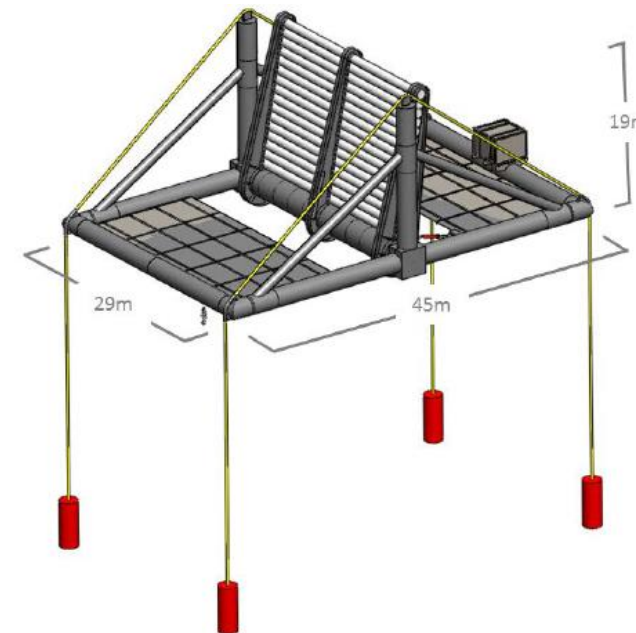
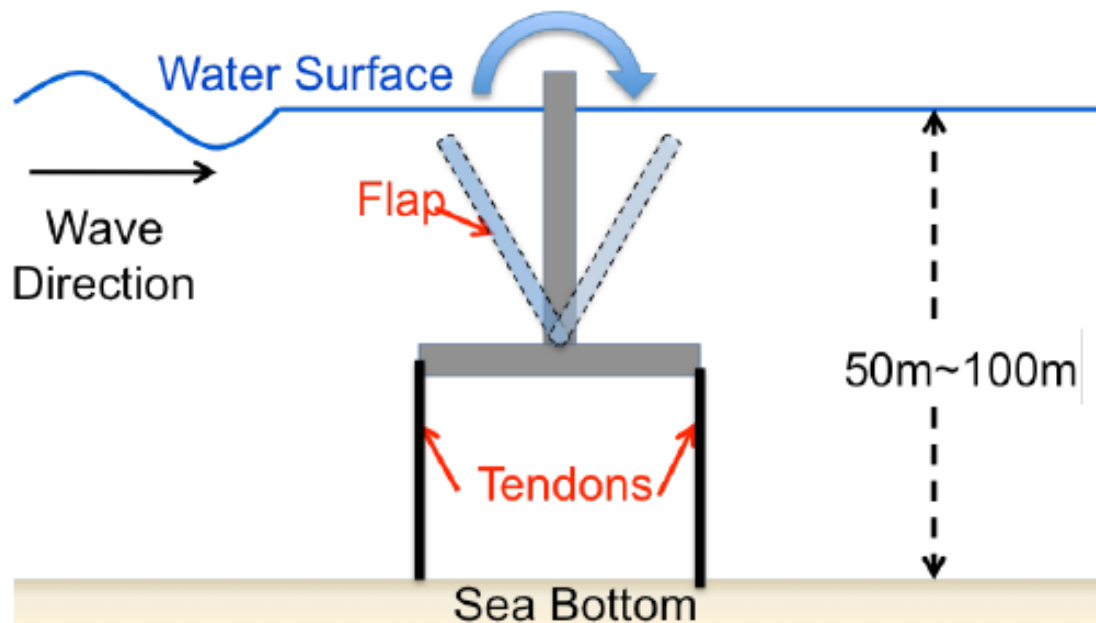
(c) AEP:

30% Capacity factor
Losses: Wake 0%, Grid 2%,
Availability 95%, Other 0%.
2,447 h/year at rated power

(d) Economics:
FCR of 10%

LCOE: Wave energy converters (II)

RM5: Oscillating Surge Wave



CASE STUDY

(a) Turbine:

Rated power for 1 machine 360kW
Flap dimensions 25 m x 19 m
Rotation shaft diameter 3 m
Water depth 50-100 m

(b) Farm:

36-MW project size
(100 machines)
Distance from shore < 30 km

(c) AEP:

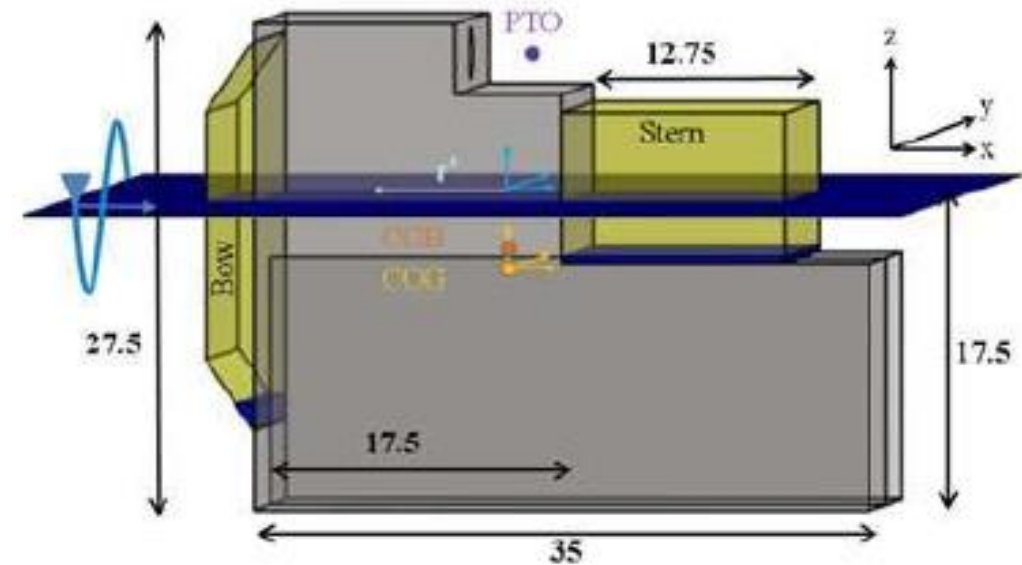
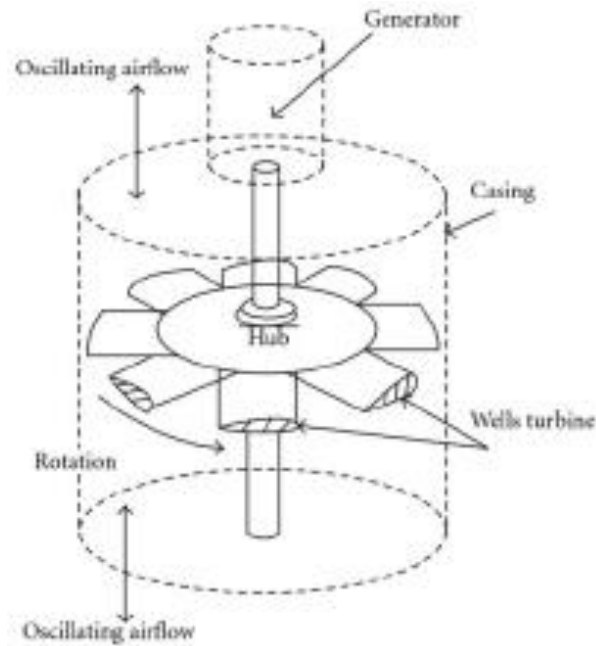
30% Capacity factor
Losses: Wake 0%, Grid 2%,
Availability 95%, Other 0%.
2,447 h/year at rated power

(d) Economics:

FCR of 10%

LCOE: Wave energy converters (III)

RM6: Oscillating Water Column



CASE STUDY

(a) Turbine:

Rated power for 1 machine 373 kW
Wells air turbine diameter 3 m
Water depth 40-100 m

(b) Farm:

37.3-MW project size
(100 machines)
Distance from shore < 30 km

(c) AEP:

27.7% Capacity factor
Losses: Wake 0%, Grid 2%,
Availability 95%, Other 0%.
2,259 h/year at rated power

(d) Economics:

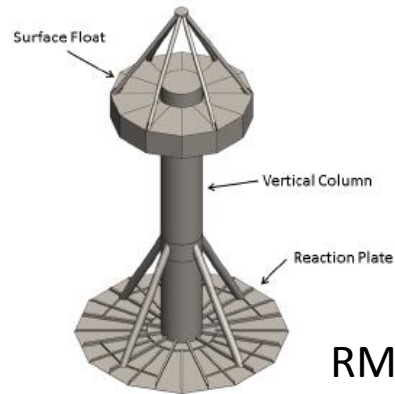
FCR of 10%

LCOE: Wave energy converters (IV)

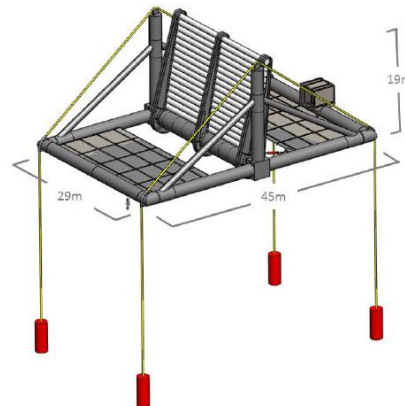
Control Co-Design
"Control to substitute materials"

Given previous assumptions we obtained:

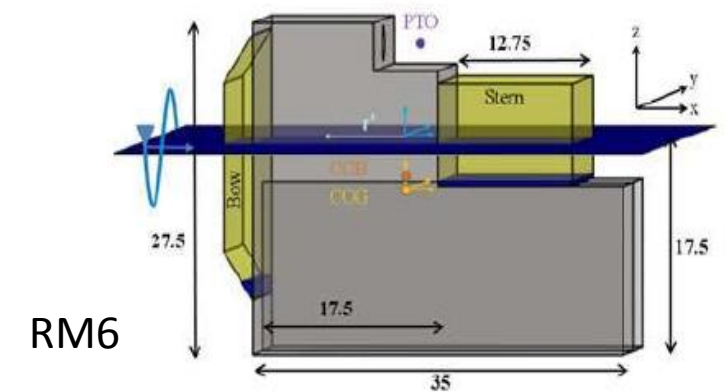
				M\$ per machine in a 100 machines farm			% of CAPEX that is:			Effects of Control Co-Design. LCOE reduction (%)			
	Name	LCOE (cts\$/kWh) with export cables 0-30 km	Power per machine (kW)	CAPEX (M\$)	OPEX (M\$/yr)	DECEX (M\$ last yr)	Steel cost	Mooring System Cost water depth 20-750 m	Installation Cost Turbine, Substructure and Mooring System	Effect of 50% mass reduction on LCOE (%)	Effect of turbulence and wake control (efficiency) on LCOE (%)	Effect of OPEX reduction of 15% (fatigue attenuation) on LCOE (%)	Total effect on LCOE. Best case scenario (%)
RM3	Wave Point Absorber	76.00	286	3.90	0.09	0.38	51.33	10.73	5.52	26.22	3.55	2.79	32.57
RM5	Oscillating Surge Wave	69.20	360	4.97	0.07	0.38	43.98	13.55	4.33	26.11	3.55	1.86	31.52
RM6	Oscillating Water Column	106.00	373	8.26	0.07	0.38	57.12	7.86	2.61	30.54	3.55	1.13	35.23



RM3



RM5



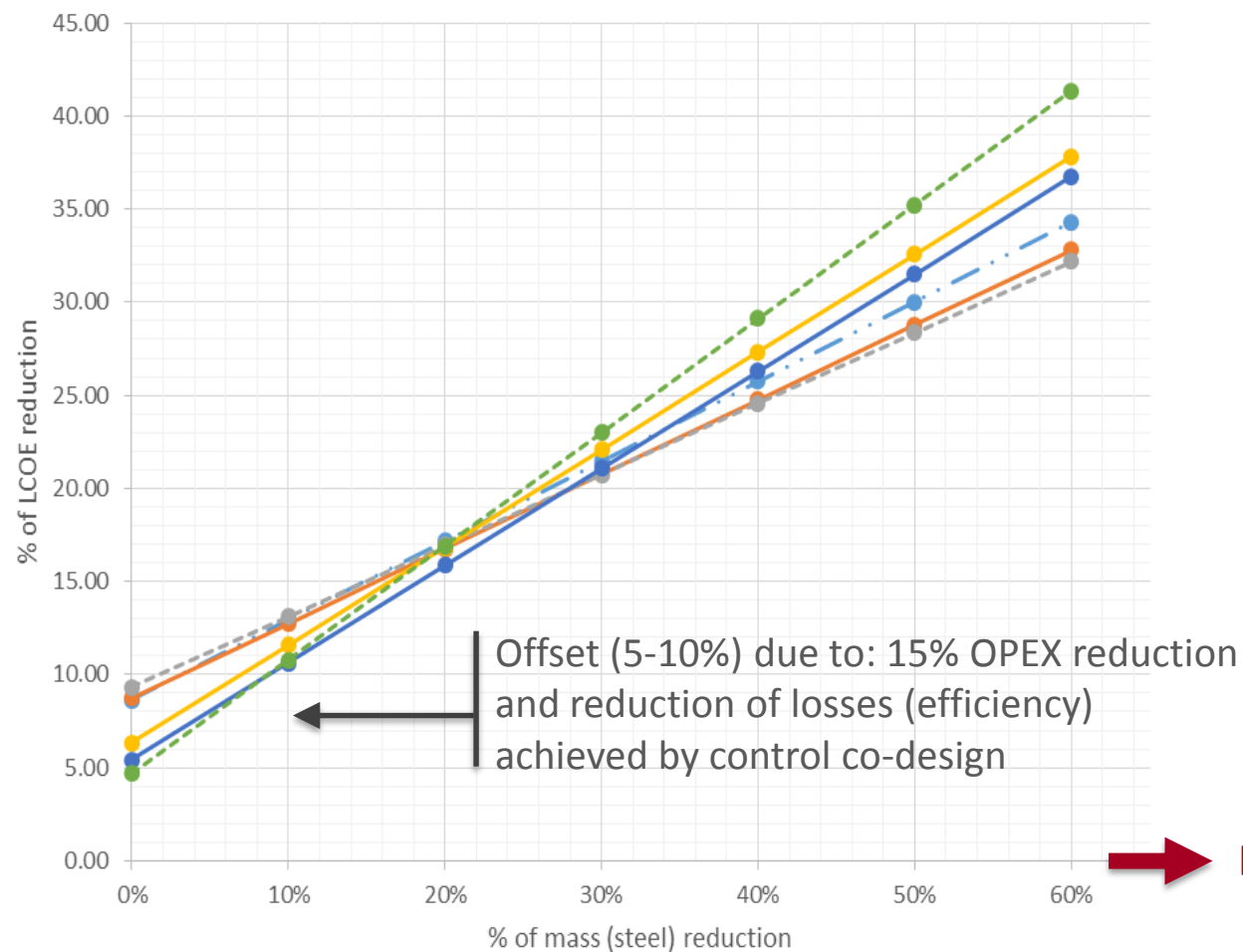
RM6

[1]. Vincent S. Neary, Mirko Previsic, et al., *Methodology for Design and Economic Analysis of Marine Energy Conversion (MEC) Technologies*. Technical Report SAND2014-9040, March 2014.

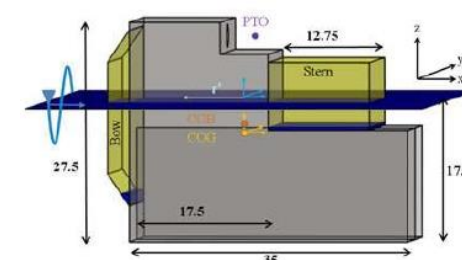
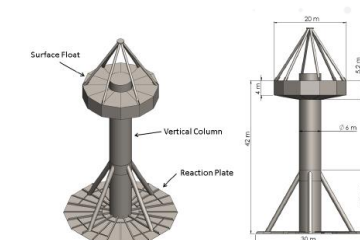
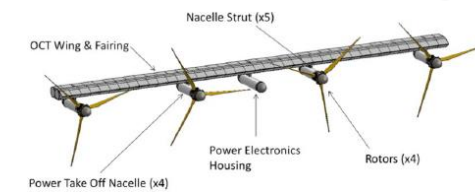
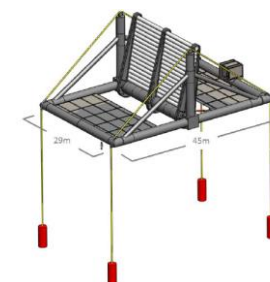
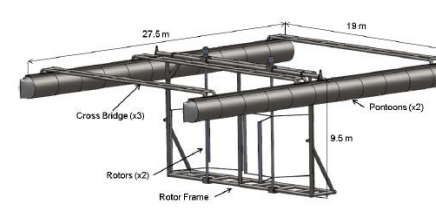
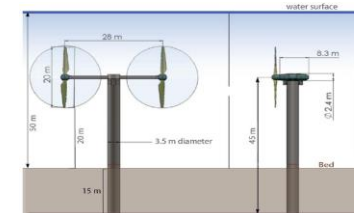
LCOE: Tidal and Wave energy converters

Given previous assumptions we obtained:

Effect of Control Co-Design on Tidal and Wave Power (export cables included)



- Tidal Turbine
- Ocean Turbine
- River Turbine
- Wave Point Absorber
- Oscillating Surge Wave
- Oscillating Water Column



DISCUSSION, COMMENTS?

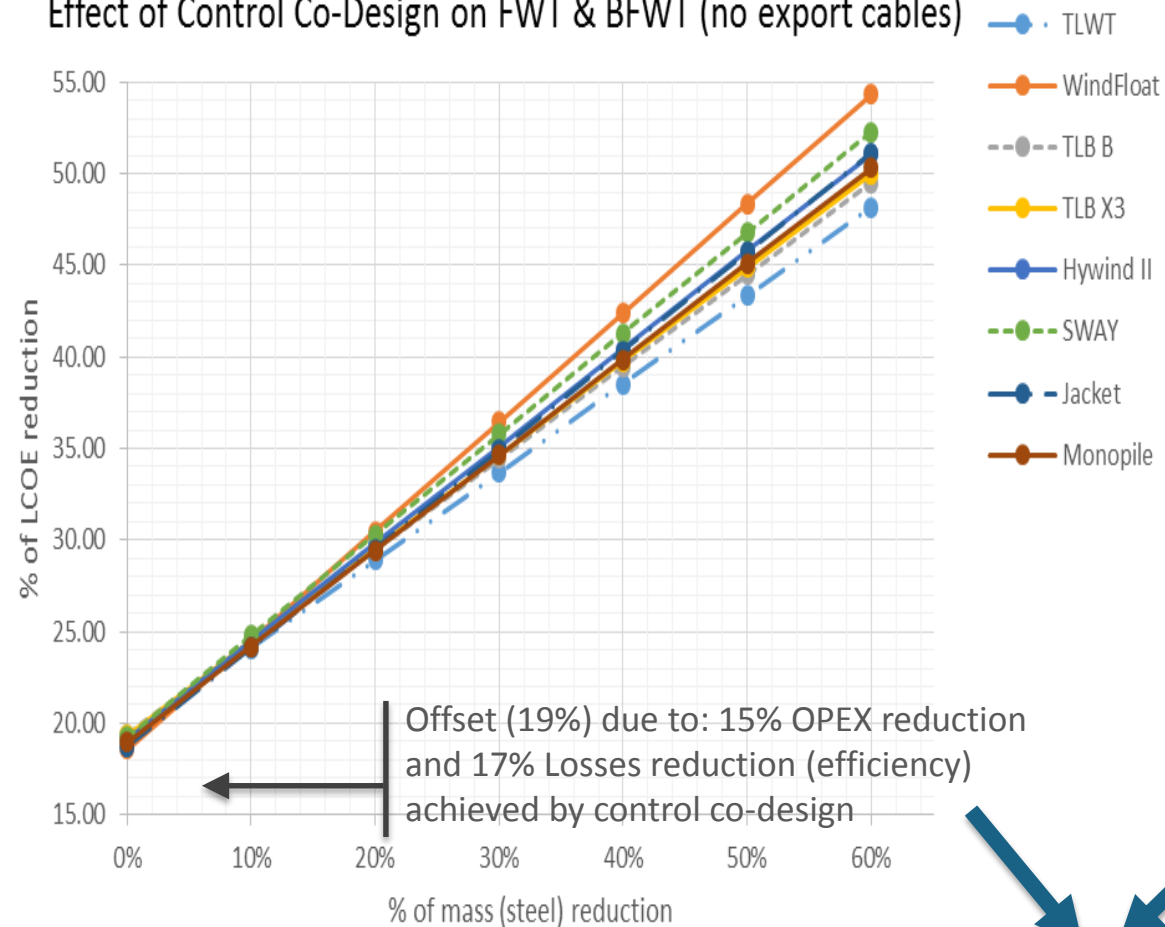
Control Co-Design
"Control to substitute materials"

LCOE: Summary. Wind/Tidal/Wave

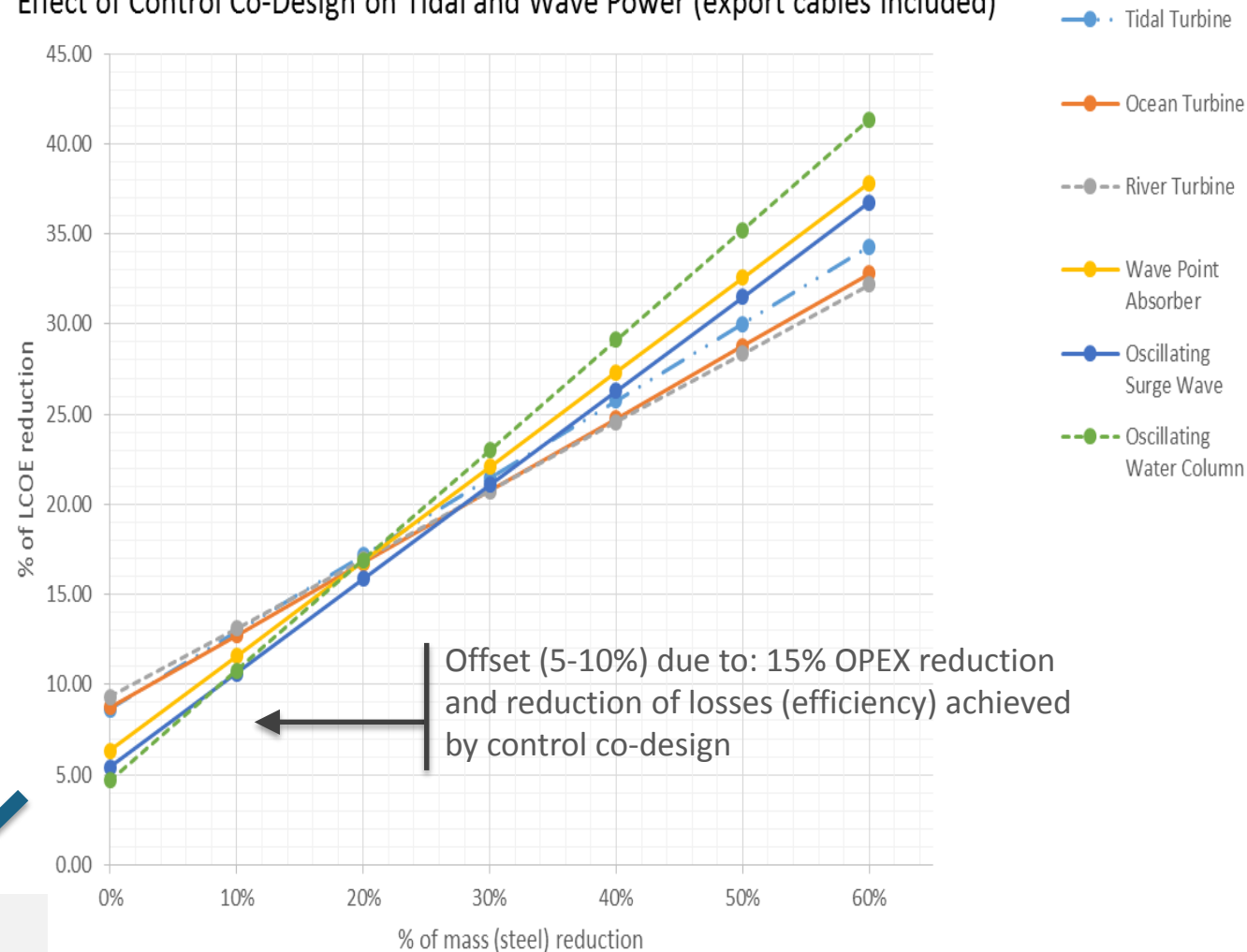
Control Co-Design
"Control to substitute materials"

Given previous assumptions we obtained:

Effect of Control Co-Design on FWT & BFWT (no export cables)



Effect of Control Co-Design on Tidal and Wave Power (export cables included)



**1% LCOE reduction every
2% of Mass (steel) reduction
in all technologies (and with previous assumptions)!!!**

Workshop: Agenda / Your feedback!!

PROJECT CASES (1H 15MIN)

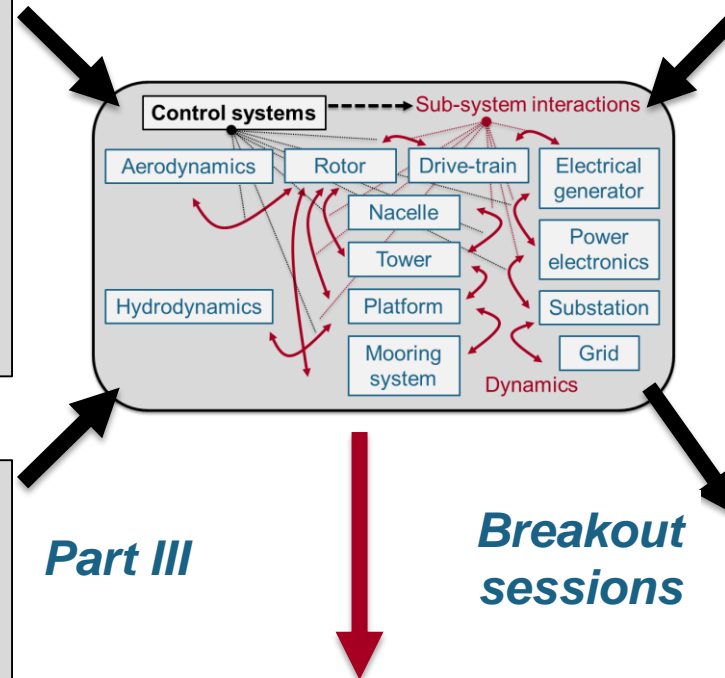
- Offshore floating wind turbine project.
Brandon Ennis, Giorgio Bacelli. (Sandia Lab)
- Tidal energy converter project.
Shreyas Mandre. (Brown Univ.)
- Wave energy converter project.
Alex Hagmuller. (AquaHarmonics)

PRINCIPLES AND METHODOLOGIES (45MIN)

- Application of control principles to co-design.
Tuhin Das. (Univ. Central Florida)
- Co-optimization for co-design.
James Alliston. (Univ. Illinois, U.C.)
- Co-simulation for co-design.
Brian St. Rock. (UTRC)

Part I

Part II



Part III

Breakout sessions

WE NEED YOUR FEEDBACK!!

- Opportunities
- Challenges/Solutions
- Control Co-Design Program...

VISION AND OPPORTUNITIES (1H 40MIN)

- Offshore floating wind turbines: a new approach. **Saul Griffith.** (OtherLab)
- Wind energy systems: vision for onshore and offshore. **Alan Wright.** (NREL)
- Airborne wind energy systems: vision and co-design. **Chris Vermillion.** (NCSU)
- Tidal energy converters: vision and projects. **Jarlath McEntee.** (ORPC)
- Wave energy converters: vision and opportunities. **Giorgio Bacelli.** (Sandia Lab)

1. Offshore
Floating Wind
Turbines

2. Offshore,
Onshore and
Airborne Wind

3. Tidal Energy
Converters

4. Wave Energy
Converters